

Passive harmonic mode-locking by mode selection in Fabry-Perot diode lasers with patterned effective index

D. Bitauld, S. Osborne, and S. O'Brien

Tyndall National Institute, University College, Lee Maltings, Cork, Ireland

We demonstrate passive harmonic mode-locking of a quantum well laser diode designed to support a discrete comb of Fabry-Perot modes. Spectral filtering of the mode spectrum was achieved using a non-periodic patterning of the cavity effective index. By selecting six modes spaced at twice the fundamental mode spacing, near-transform limited pulsed output with 2 ps pulse duration was obtained at a repetition rate of 100 GHz.

The generation of high power, ultrashort optical pulses using mode-locked diode lasers is of considerable importance across a range of applications in optical communication systems and data processing [1, 2]. In recent years, the wide gain bandwidth of certain self-assembled gain materials has enabled sub-picosecond and femtosecond pulsewidths to be obtained [3–5]. In parallel, various techniques such as colliding pulse mode-locking (CPML) and harmonic mode-locking have been adapted for diode lasers that allow higher repetition rates to be achieved while avoiding the lower average power associated with short device lengths [1].

CPML places the saturable absorber section at the center of the cavity. Two counterpropagating pulses are formed and collide at the center. In this way the saturation of the absorption is enhanced and the repetition rate is simultaneously doubled from the fundamental [6]. Harmonic mode-locking of diode lasers can be achieved by forcing the device to lock on a set of equally spaced but non-adjacent cavity modes. With this approach, terahertz (THz) repetition rates have been achieved in devices that incorporate distributed Bragg reflector mirrors [7] and intra-cavity reflectors [8]. A limitation of these approaches to harmonic mode-locking however is the fact that only the harmonic frequency rather than the precise form of the mode-locked spectrum itself can be specified.

In this letter we demonstrate an approach to passive mode-locking of diode lasers based on the selection of individual modes from the spectrum of Fabry-Perot resonances. Mode selection is achieved by a distributed reflection mechanism that is designed as a perturbation of the Fabry-Perot mode spectrum. Such an approach has some features in common with that described in [8], although, in our case the effective index profile along the device is derived directly from an inverse problem solution. This approach has allowed us to design single-mode [9], and two-mode Fabry-Perot diode lasers [10] with high spectral purity and can in principle provide a much greater degree of control of the mode-locked spectrum of the laser. To demonstrate passive mode-locking of a discrete comb of Fabry-Perot modes, a saturable absorber section is placed adjacent to one of the cavity mirrors. In the device we consider here, six primary modes are chosen with a spacing of two fundamental modes leading to mode-locking at the first harmonic of the cavity.

We have shown that a set of self-consistent equations

for the lasing modes can be found by making an expansion about the cavity resonance condition in a Fabry-Perot laser [11]. The effective index along the Fabry-Perot cavity is modified by N additional features that are described by an index step Δn . In our case, these features are slotted regions etched into the ridge waveguide of the device. We assume that the index step, Δn , associated with the etched features is a real quantity, although some scattering losses are inevitably introduced that strongly depend on the depth of the slotted region [12]. The threshold gain, γ_m , can then be expressed at first order in the index-step as $\gamma_m = \gamma_m^{(0)} + (\Delta n/n)\gamma_m^{(1)}$. Here $\gamma_m^{(0)}$ are the mirror losses of the unperturbed cavity and the function $\gamma_m^{(1)}$ describes the effect of the coupling of each feature to the cavity mirrors. We choose a particular mode m_0 as an origin in wavenumber space. If we then assume that the features are positioned such that at the frequency of mode m_0 , a half wavelength subcavity is formed between each feature and one of the cavity mirrors, this function takes a particularly simple form:

$$\gamma_m^{(1)} = \frac{1}{L_c \sqrt{r_1 r_2}} \cos(m_0 \pi) \cos(\Delta m \pi) \times \sum_{j=1}^N A(\epsilon_j) \sin(2\pi \epsilon_j m_0) \cos(2\pi \epsilon_j \Delta m). \quad (1)$$

In the above expression, the factor $A(\epsilon_j) = r_1 \exp(\epsilon_j L_c \gamma_m^{(0)}) - r_2 \exp(-\epsilon_j L_c \gamma_m^{(0)})$ and ϵ_j is the fractional position of the center of each feature measured from the center of the cavity.

Eqn. 1 above allows Fourier analysis to be used to make a direct connection between the index profile in real space and the threshold gain modulation in wavenumber space. Here we consider a device with six primary modes and a primary mode spacing of $a = 2$ fundamental cavity modes (first harmonic). Neglecting frequency dispersion, the appropriate filtering function is then a series of equally spaced sinc functions, as each sinc function naturally selects a single mode while leaving all others unperturbed. Selecting modes in pairs that are centered at the origin chosen in wavenumber space, the Fourier transform of the threshold gain modulation function is $\cos(\pi a \epsilon) + \cos(3\pi a \epsilon) + \cos(5\pi a \epsilon)$ for $-1/2 \leq \epsilon \leq 1/2$ and is zero otherwise. Multiplying this Fourier transform function with the envelope function $[A(\epsilon)]^{-1}$, we obtain the feature density function shown in Fig. 1 (a).

The feature density function shown is then sampled in

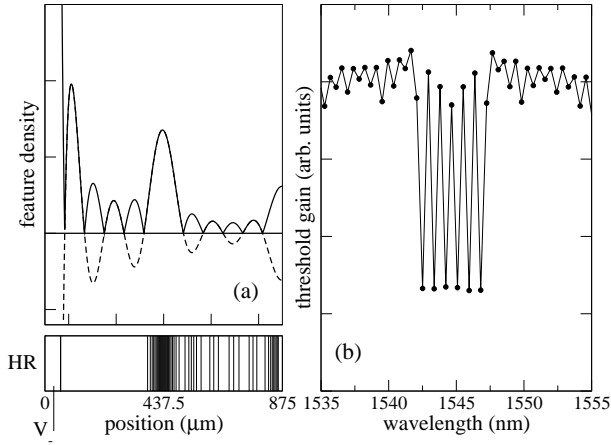


FIG. 1: (a) Feature density function (solid line). Dashed lines indicate intervals where the Fourier transform of the spectral filtering function chosen is negative. (b) Calculation of the threshold gain of modes for the laser cavity schematically pictured in the lower panel of the figure. Lower panel: Laser cavity schematic indicating the locations of the additional features. The device is high-reflection (HR) coated and includes a saturable absorber section adjacent to the HR mirror as indicated.

order to define the appropriate effective index profile [11]. The cavity is asymmetric with one high-reflection coated mirror, and features are placed on the opposite side of the device center to this mirror where the feature density function is more uniform. This is possible because only positive Fourier components are required to form the desired threshold gain variation in the case considered. Note also that at each zero of the feature density function, a $\pi/2$ phase shift is introduced into the effective index profile. The low-density grating structure that results is then related to a superstructure Bragg grating that is modulated by a series of lower spatial frequencies. A schematic picture of the device, high-reflection coated as indicated, is shown in the lower panel of Fig. 1 (a), where $N = 48$ etched features are introduced. The calculated form of the threshold gain spectrum is shown in Fig. 1 (b). One can see that six modes are selected around a central wavelength of 1545 nm. The comb of selected modes spans a bandwidth in frequency of 500 GHz for a device length of 875 μm .

We now present experimental data obtained from a ridge waveguide Fabry-Perot laser fabricated to the design depicted in Fig. 1. These data serve to illustrate how the mode selection mechanism plays an important role in two distinct dynamical states of the device, which is a multi-quantum well InP/InGaAlAs laser with a peak emission near 1.5 μm . A saturable absorber section of length 60 μm was placed adjacent to the high reflectivity mirror. During the measurements the temperature of the device was stabilized at 15°C.

Fig. 2 displays the optical spectrum obtained for a reverse bias of -2.15 V applied to the saturable absorber section of the device. In this case the dynamics are

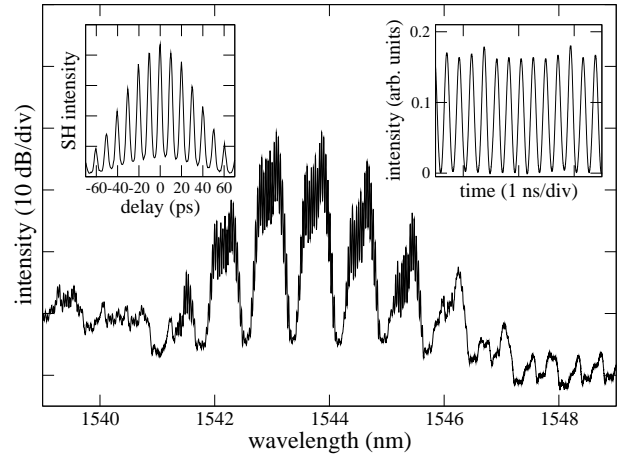


FIG. 2: Optical spectrum for a voltage of -2.15 V across the saturable absorber section. The current in the gain section is 120 mA. Left inset: Autocorrelation measurement showing Q-switched mode-locking. Right inset: Intensity time trace showing a large amplitude modulation of the total intensity.

dominated by a set of strongly broadened modes that are spaced at twice the fundamental Fabry-Perot mode spacing. Interestingly, we do not observe precisely six of these dominant modes but rather there are five dominant modes with a well developed internal structure and a pair of much weaker satellites. The autocorrelation measurement shown in the left inset indicates that the dynamical state of the device is Q-switched mode-locking in this case, where bunches of mode-locked pulses are emitted [13]. A measurement of the time trace of the total intensity of the laser is shown in the right inset, which shows a strong intensity modulation on a nanosecond time scale. This time scale determines the spacing of the individual peaks that make up each of the broadened Fabry-Perot modes.

Mode-locking was observed with a voltage of -2.20 V applied to the saturable absorber section. The mode-locked spectrum is shown in Fig. 3 where a comb of modes at a frequency separation of 100 GHz dominate the spectrum. In this case, more than the original six primary modes that were selected have significantly more power than the background modes. We attribute this broadening of the spectrum to power transfer by four-wave mixing. The Gaussian fit to the intensity profile over a bandwidth of eight modes that was used to calculate the full width half-maximum (FWHM) is shown in the figure.

The corresponding intensity autocorrelation is shown in the insets of Fig. 3. The left inset demonstrates that well separated pulses are obtained at 100 GHz repetition rate, while on the right a Gaussian fit to a single pulse is shown. From the FWHM of the optical spectrum (1.76 nm) and the deconvolved pulsewidth of 2.06 ps, we obtain a time-bandwidth product $\Delta\nu\Delta\tau \sim 0.46$, which is close to the Fourier limited value of ~ 0.44 . We note that at 220 GHz, the FWHM of the optical spec-

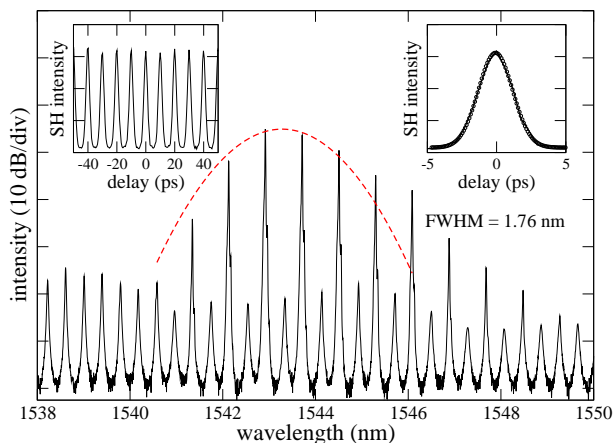


FIG. 3: Optical spectrum for a voltage of -2.20 V across the saturable absorber section. The current in the gain section is 120 mA. The dashed line is a Gaussian fit to the spectrum of modes at the first harmonic over the bandwidth indicated. Left inset: Autocorrelation measurement showing pulsed output at 100 GHz repetition rate. Right inset: Autocorrelation measurement with Gaussian fit.

trum is approximately equal to half of the bandwidth spanned by the comb of modes selected. Because the mode selection mechanism acts to predetermine the carrier wave frequency, we expect that shorter pulses may be obtained where the position of the central mode m_0 is optimized with respect to the material gain and loss dispersion. This conclusion is supported by the observation that otherwise identical Fabry-Perot devices will mode-

lock for different values of the drive parameters and with significantly detuned carrier wave frequencies.

We note also finally that while we have chosen to select a comb of six modes with uniform thresholds in the device considered here, our approach gives great freedom to tailor the spectrum of the mode-locked device. The choice of spectral filtering function can be regarded as an additional degree of freedom that determines not only the repetition rate but also the pulse shape and duration. For example, the generation of pulses with approximately square profile should be possible, while some pulse shortening should be also possible through tailoring of the linear modal losses in order to compensate for the material gain dispersion. In addition, our approach will allow a minimal set of locked modes to be selected, which will enable optical synthesis of THz and millimeter wave frequencies to be achieved.

In conclusion, we have demonstrated passive harmonic mode-locking of a comb of discrete Fabry-Perot modes in a diode laser that incorporates a non-periodic effective index profile. Near transform limited pulses of 2 ps duration were obtained at 100 GHz repetition rate. Our results demonstrate an interesting alternative approach to harmonic mode-locking in diode lasers with significant potential applications in optical waveform and frequency synthesis.

Acknowledgments. This work was supported by Science Foundation Ireland and Enterprise Ireland. The authors thank Eblana Photonics for the preparation of sample devices.

-
- [1] E. A. Avrutin, J. H. Marsh, and E. L. Portnoi, *IEE Proc. Optoelectron.* **147**, 251 (2000).
 - [2] K. A. Williams, M. G. Thompson, and I. H. White, *New Jour. Phys.* **6**, 179 (2004).
 - [3] E. U. Rafailov, M. A. Cataluna, W. Sibbett, N. D. Il'inskaya, Y. M. Zadiranov, A. E. Zhukov, V. M. Ustinov, D. A. Livshits, A. R. Kovsh, and N. N. Ledentsov, *Appl. Phys. Lett.* **87**, 081107 (2005).
 - [4] Z. G. Lu, J. R. Liu, S. Raymond, P. J. Poole, P. J. Barrios, and D. Poitras, *Opt. Express* **16**, 10835 (2008).
 - [5] K. Merghem, A. Akrou, A. Martinez, G. Aubin, A. Ramdane, F. Lelarge, and G.-H. Duan, *Appl. Phys. Lett.* **94**, 221107 (2009).
 - [6] Y. K. Chen, M. C. Wu, T. Tanbun-Ek, R. A. Logan, and M. A. Chin, *Appl. Phys. Lett.* **58**, 1253 (1991).
 - [7] S. Arahira, S. Oshiba, Y. Matsui, T. Kunii, and Y. Ogawa, *Optics Lett.* **19**, 834 (1994).
 - [8] D. A. Yanson, M. W. Street, S. D. McDougall, I. G. Thayne, J. H. Marsh, and E. A. Avrutin, *IEEE J. Quantum Electron.* **38**, 1 (2002).
 - [9] S. O'Brien and E. P. O'Reilly, *Appl. Phys. Lett.* **86**, 201101 (2005).
 - [10] S. O'Brien, S. Osborne, K. Buckley, R. Fehse, A. Amann, E. P. O'Reilly, L. P. Barry, P. Anandarajah, J. Patchell, and J. O'Gorman, *Phys. Rev. A* **74**, 063814 (2006).
 - [11] S. O'Brien, A. Amann, R. Fehse, S. Osborne, E. P. O'Reilly, J. M. Rondinelli, *J. Opt. Soc. Am. B* **23**, 1046 (2006).
 - [12] Q. Y. Lu, W. H. Guo, R. Phelan, D. Byrne, J. F. Donegan, P. Lambkin, and B. Corbett, *IEEE Photon. Tech. Lett.* **18**, 2605 (2006).
 - [13] P. Vasil'ev, *Ultrafast Diode Lasers: Fundamentals and Applications* (Artech House, Boston, 1995).